Determination of angle of internal friction for biomass

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Masses of dry and not sticky solid particles have many of the properties of fluid such as exerting pressure on the sides and walls of a container and flowing through opening. However they differ from liquids and gases in several ways as mentioned below:

?? Due to interlocking nature of particles, the pressure is not same in all directions. The pressure reduces with direction and is a minimum in the direction at right angles to the applied pressure.
?? A shear stress applied at the surface of a mass is transmitted throughout a static mass of particles unless failure occurs.
?? Variation in bulk density due to varied degree of compactness.

The flow behavior of solids from the bottom of a storage bin is entirely different from those of liquids and gases.

When the outlet at the bottom of a bin is opened, the solids immediately and directly above the opening begins to flow resulting downward movement of a central column of solids without disturbing the material at the sides. Eventually lateral flow begins first from the topmost layer of solids with the formation of a conical depression in the surface of the mass. The material slides laterally into the central column at an angle approximating the angle of internal friction of the solids a_m. If additional material is added to the top of the bin at the same rate as material is flowing out of the bottom, the solids near the walls remain stagnant and do not discharge no matter how long flow persists.

Therefore the flow rate of granular solids by gravity through a circular opening depends on the diameter of the opening and on the properties on the solids and not on the height of the bed of solids.

Biomass do suffer from two major constraints i.e., their high moisture contents and relatively low bulk density. These constraints inhibit their economical transportation over a long distances, thereby necessitate their utilization near the sources of production. Also these constraints play a major role in the storage and handling of biomass.

Most of the gasifiers in operation use either wood chips or palletized biomass as it's fuel in order to maintain steady flow of biomass without arching. The chipping or briquetting consumes considerable amount of energy resulting in reduction of net available energy from biomass.

Mc.cabe and Smith (1967) relates the various parameters and properties of solid particles for flow in the range of 4 to 20 mesh as follows [1]:

$$m = \frac{? _p D_n^o}{(6.288 \tan a_m + 23.16)(D_p + 1.889) - 44.90} \longrightarrow \text{Equation (A)}$$

It is evident from equation (A) that the angle of internal friction plays a vital role in designing the opening diameter for a given size and density of biomass.

Mc cable and Smith further derives the relationship between vertical pressure acting at the base of a bin, lateral pressure, co-efficient of frictions of wall and particles as follows [2]:

$$p_B = \frac{r\ ?_b\ (g/g_c)}{2?^1 k^1} \quad [\,1\text{- exp}\,(-2?^1 k^1 z_t/r)] \longrightarrow \text{Equation (B)}$$

With many solids, equation (B) indicates that when the height reaches about 3 times the diameter of the bin, the additional material has virtually no effect on the pressure at the base.

The experimental set-up consists of a graduated transport cylinder with both ends open. Another cylindrical plastic container closed at the bottom, fitted with a flexible membrane at the top and a side tube at the bottom is taken. The diameter of this container is slightly smaller then the diameter of the graduated tube so that the membrane and of the container may be inserted tightly in to the cylinder. The side tube is connected to an inclined manometer so as to enable to read even very low-pressure difference.

The vertical pressure P_B acting on the membrane for every incremental addition of biomass in to the cylinder is measured from the manometer, when the height of the solid particles Z_t is increased more than 3 times the diameter of the cylinder, no change in P_B is observed in accordance to equation (B).

After estimating the parameters such as $?_b$, radius and μ^1 in the conventional way the value of k^1 is determined by trial and error using p_b, z_t data. From k^1, the angle of internal friction a_m is calculated using the equation $\sin a_m = (1-k^1) / (1+ k^1)$.

Nomenclature

m	=	Solid flow rate (lb/min)
D_o	=	Opening diameter (inches)
a_m	=	Angle of internal friction of solids
D_p	=	Particle diameter (inches)
p_B	=	Vertical pressure at the base (lb_f/ft^2)
$?^1$	=	Coefficient of friction (dimensionless)
K^1	=	Ratio of normal pressure to applied pressure (p_L/p_V)
r	=	Radius of bin (ft)
$?_b$	=	Bulk density (lb/ft^3)
g	=	Gravitational acceleration (ft/sec^2)
g_c	=	Newton's law conversion factor, 32.174 ($ft\text{-}lb/\ lb_f\text{-}sec^2$)
Z_T	=	Total height of solids (ft)

Reference

McCabe and Smith J C, "Unit Operations of Chemical Engineering", McGraw Hill, II edition (1967), [1] pp. 806, [2] pp. 804